New Strong, Tough, and Creep-Resistant Ceramic Developed

Control of Nanoscale Grain Boundary Properties Key to Achieving Improvements

A research group under the direction of Lutgard De Jonghe and Robert Ritchie has developed a new silicon-carbide-based ceramic with an unprecedented combination of high toughness, strength, and resistance to creep. The breakthrough was achieved by controlling the grain boundary chemistry and structure on the nanometer scale.

Advanced ceramics, and particularly high temperature structural ceramics, can enable a range of efficient energy technologies. However, their use in these applications has been hampered by deficiencies in their mechanical properties, in particular strength (applied load at which the material breaks, measured in MPa), toughness (the minimum "stress intensity factor" at which cracks propagate, in MPa $m^{1/2}$ and creep strength (resistance to slow deformation at constant temperature under a given load, measured in MPa). Various methods have been developed to improve some of these mechanical properties but achieving the right combination has been difficult. For example, grain boundary engineering has been used to improve strength and toughness, but the resulting ceramics have had unacceptably low creep resistance at high temperatures. Conversely, attempts to increase high temperature creep resistance have reduced the ceramic's toughness and strength.

The Berkeley group overcame these difficulties by developing a new microstructured ceramic material. They began by developing a series of silicon carbide ceramics with an interlocked grain structure induced by the addition of aluminum, carbon, and boron (MSD Highlight 95-10). The interlocked grains make it difficult for cracks to propagate, improving the material's toughness, to 5-9 MPa $m^{1/2}$ (see figure), well above that of a commercial SiC ceramic (3 MPa $m^{1/2}$). Next, the team introduced nanoscale films of aluminum-based compounds in the grain boundaries, and crystallized them with a high temperature heat treatment. Most notably, the treatment improved the room temperature strength by 30% and the strength at 1300°C by a factor of four. Specifically, at all loads tested, the creep strength was improved most dramatically at higher applied loads (see figure). This new material displays the highest fracture toughness ever reported for a silicon carbide ceramic, and requires a rising stress intensity to cause crack propagation, comparing favorably to the commercial SiC ceramic which does not. In addition, it has far superior resistance to cyclic loading (measured in terms of the fatigue threshold in MPa $m^{1/2}$) compared to a commercial SiC ceramic at all temperatures from ambient to 1300°C. The new ceramic is called ABC-SiC for the aluminum, boron, and carbon additives that help it to achieve its desirable combination of mechanical properties.

This work demonstrates again that a thorough understanding of the mechanisms underlying the mechanical properties of a material, here SiC, and the ability to control micro- and nanostructure, allows high-strength, high-toughness and creep-resistant ceramics to be developed. Moreover, in applications where the fatigue is the critical design parameter, such as turbine blades, ABC-SiC can even outperform traditional metallic alloys such as Ti-6Al-4V due to its higher fatigue threshold. The methodology used here may be more general; the investigators believe that the development of three-dimensional, interlocking grain microstructures with appropriately controlled grain boundary chemistries can be successfully applied to promote simultaneously high strength, toughness, and creep resistance in a wide variety of brittle materials. The development of high temperature ceramics with this array of desirable mechanical properties should allow their use in high temperature combustion and other energy conversion applications with increased efficiency.

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